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A Combat Simulation Analysis of Autonomous Legged Underwater Vehicles

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Autonomous Legged Underwater Vehicles (ALUVs) are inexpensive crab-like robotic prototypes which will systematically hunt and neutralize mines en masse in the very shallow water and the surf zone (VSW/SZ). With the advent of mine proliferation and the focal shift of military power to the littorals of the world, ALUVs have the potential to fill a critical need of the United States Navy and Marine Corps mine countermeasure (MCM) forces.

Duplicating the MCM portion of the Kernel Blitz 95 exercise whenever feasible, this thesis uses the Janus interactive combat wargaming simulation to model and evaluate the effectiveness of the ALUV as a MCM. Three scenarios were developed: an amphibious landing through a minefield using no clearing/breaching; an amphibious landing through a minefield using current clearing/breaching techniques; and an amphibious landing through a minefield using ALUVs as the clearing/breaching method.

This thesis compares the three scenarios using landing force kills, cost analysis and combat power ashore as measures of effectiveness.

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A COMBAT SIMULATION ANALYSIS OF AUTONOMOUS LEGGED UNDERWATER VEHICLES

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INTRODUCTION

The strategic concept and direction of the Naval Service provide compelling requirements for effective and modern mine warfare forces, these needs are outlined in the September 1992 white paper titled "...From the Sea," and reaffirmed in its October 1994 companion document titled "Forward ...From the Sea." The Naval Service must be prepared to operate in distant waters in the early stages of regional hostilities to enable the flow of land-based air and ground forces into the theater of operations. It must also be able to protect vital follow-on sealift required for delivering heavy equipment and sustaining major forces (Office of the Chief of Naval Operations 1995).

A highly flexible force, called a Naval Expeditionary Force (NEF) must achieve forcible entry onto hostile shores by projecting Marine landing forces (LF) to objectives ashore. The NEF must reach inland rapidly, finding gaps in the enemy coast defenses or, if necessary, penetrating prepared beach defenses. As described in the above mentioned documents, operations in these littoral regions expose the NEF to areas in which adversaries can concentrate and layer their defenses including the use of mines.

Today's NEF must capitalize on its inherent power, speed, agility, flexibility, mobility, and self sustainment to project power ashore using the principles of maneuver warfare. The adaptation of this warfare style and its principles to a maritime campaign is termed "operational maneuver from the sea" (OMFTS). Integral to the concept of OMFTS is the concept of over-the-horizon (OTH) amphibious operations that use technology advances to improve the

opportunity for tactical surprise. Under the concept of OTH amphibious operations, Landing Crafts Air Cushioned (LCACs) and Amphibious Assault Vehicles (AAVs) deliver the LF across the very shallow water and the surf zone (VSW/SZ). Although discovery of gaps in the enemy's mine and obstacle defense is desirable, the in-stride breaching of those defenses may be necessary to facilitate the surface assault.

Effective in-stride breaching can eliminate some of the delays that the LF may encounter and minimizes the potential for losing the element of surprise (Naval Surface Warfare Center 1995). However, current mine countermeasures (MCM) capabilities are limited by inadequate integration of assets, minimal reconnaissance means (especially clandestine), and operational pauses created by the slow, deliberate nature of MCM operations. The result is that an enemy who can emplace mines in operationally significant littoral locations has a distinct advantage.

One proposed solution to the problem of in-stride breaching is to employ a large number of small, inexpensive, expendable robotic units that crawl on the ocean bottom, hunting and neutralizing mines. Such a system comprising a large number of identical and inexpensive vehicles is more robust than a system that relies on a very few more complex vehicles, as mission success is not significantly impacted by the loss of a reasonable percentage of units. Additionally, satisfactory area coverage can be accomplished in part by the sheer numbers of vehicles rather than a requirement of systematic, thorough, time consuming search (Guillebeau 1995).

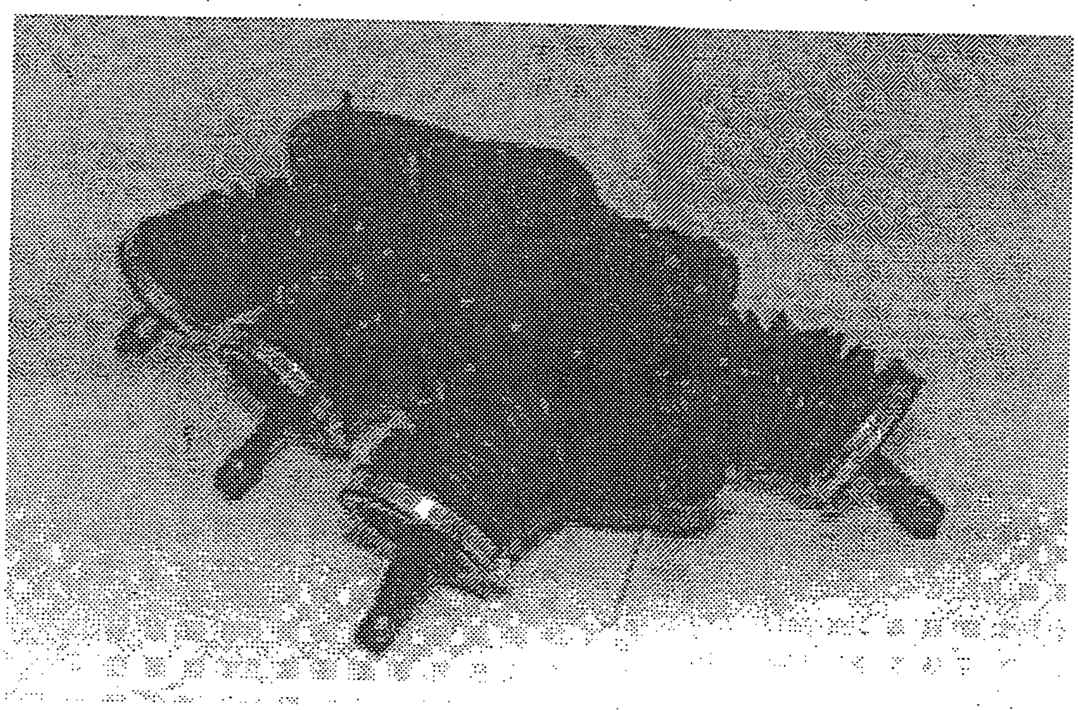

Figure 1. Autonomous Legged Underwater Vehicle (ALUV)

One technology that shows potential as a robotic solution to the MCM problem is Autonomous Legged Underwater Vehicles (ALUVs), as shown in Figure 1. Currently,

the Advanced Research Projects Agency and the Office of Naval Research are funding a consortium consisting of Rockwell International, IS Robotics, and the University of California at Berkeley to jointly develop ALUVs for VSW/SZ mine hunting and *en masse* neutralization. ALUVs scuttle along the surf bottom in the VSW/SZ and after encountering a mine, cling to it awaiting a detonation command from an operations center aboard a landing craft offshore. Once the signal is given, each ALUV blows itself and the attached mine apart. Detailed information regarding the ALUV can be found in Elsley, et al 1995.

The purpose of our research is to evaluate the tactical effectiveness of the ALUV as a mine countermeasure in the very shallow water (10 to 40 feet) and in the surf zone (high water mark to 10 feet). More specifically, we want to make a meaningful comparison of this new technology to current Naval Service (Navy and Marine Corps) MCM capability for hunting and neutralizing mines in these regions. To achieve this goal we went beyond traditional search theory based statistical evaluations (e.g. percent neutralization) by using a high-resolution combat simulation (Janus). This approach allows us to go a step further and consider the operational impact of the technology, and also gives us insight into the associated tactical implications. Moreover, the level of detail afforded by such a model allows us to see how specific battlefield events influence the summary statistics.

BACKGROUND

The Naval Postgraduate School (NPS) has used the Army's Janus combat model as a means to gather information on measures of effectiveness in amphibious operations since 1991. The work by Schmidt (1994) utilized Janus in evaluating the effectiveness of different weapons packages on the Advanced Amphibious Assault Vehicle (AAAV). As a byproduct, the work used a land based combat model to model force-on-force combat in an amphibious landing. He found the model's database structure robust enough to create sea-borne assets and execute an assault by a company-sized landing force. This approach was extended by Weber (1995) to include executing an amphibious landing through a minefield. See also Wineinger (1996), Lazzell (1996), and Chen (1996) for additional research using Janus to model amphibious operations in the littorals.

The timing of this research coincided with the Advanced Concept Technology Demonstration (ACTD) which was to be conducted during a Joint Task Force Exercise (JTFEX). As part of the ACTD, there was a desire to include models that captured the force-on-force effectiveness of various MCM. During a visit to NPS, Dr. Elan Moritz, Director of Modeling and Simulations at the Coastal Systems Station, Panama City, Florida, was shown the Janus modeling that had been done to that date. He encouraged NPS participation in the ACTD simulation effort. Further discussions with Col Joe Singleton (USMC) from the Joint Countermine Program Office provided some funding to conduct this research.

THE EXPERIMENT

With the ACTD emphasis on garnering information from field exercises, this research duplicated the MCM portion of the Kernal Blitz 95 exercise. One objective of that exercise was to improve the ability of the NEF to operate effectively, as a total force, in a littoral environment (COMINEWARCOM 1995). Kernel Blitz is an umbrella exercise that contains a series of subordinate exercises that include a MCM effort.

Experimental Methodology

We created three different scenarios using the Janus (version 3.15) combat simulation. The base scenario was modeled from a key component of the Kernal Blitz 95 exercise, to a high level of detail (including use of the specific Camp Pendleton terrain). From this base we built three scenarios representing different MCM approaches. Once this task was completed we conducted a number of independent simulation runs of these three scenarios. Data were collected from the simulation runs to compare selected measures of effectiveness with a goal of determining the tactical effectiveness of ALUVs as a MCM in a simulated littoral environment and to compare the ALUV to current Naval Service littoral MCM capabilities. The Mann-Whitney U Test, a non-parametric statistical test, was used to determine if significant differences exist between the three scenarios.

Number of scenario runs

It is desirable to select a sample size that minimizes the detection of inconsequential effects and maximizes the detection of those considered important, while retaining the true characteristics of the underlying distribution of the data. Janus is a stochastic model that determines the results of actions such as detections or minefield crossing events according to the laws of probability. While it is unlikely, the interplay of probabilities could possibly generate an occurrence that is unrepresentative of what would really happen. We assume, based on many years of experience, that such an occurrence could happen once in a hundred Janus simulation runs. This implies that the probability of a successful run is $p = 0.99$.

In an effort to keep the number of runs at a reasonable level with a minimal sacrifice of precision we elected to make as many runs as are necessary to give a 95% confidence interval. In particular, we require that the maximum expected error be $E = 5\%$ and that the level of significance be $\alpha = .05$. Assuming that a random sample of successful runs is approximately standard normal when the sample size is sufficiently large and applying the Central Limit Theorem allows us to estimate n, the required number of scenario runs, using the equation below (Tannis 1987, p240):

$$n = \frac{z_{\alpha/2}^2 p(1-p)}{E^2}$$

Substituting in the appropriate values and rounding up to the nearest integer gives a required number of 16 scenario runs.

Scenarios

Over-the-horizon operations call for an approximate 20 nautical mile distance from ship to shore; however, the defensive force's ability to detect, target, and attack the LF is the key determinant of the OTH distance. The scenarios contained herein assume that the OTH operation is conducted at 1200 hours, at low tide, from a distance of 20 nautical miles from the coastline. It is further assumed the LF commander has maneuvered his LF to a strike location that is neither anticipated nor discovered by the defending force. The LF does encounter one problem, a littoral minefield in the VSW/SZ. The authors realize that rarely will a LF go undetected and that minefields are almost always covered by direct fire weapons, but as we desired to isolate MCM efforts against the minefield without the compounding interactions of an opposed landing we deliberately omitted active defensive forces from the simulation.

The defensive force employs a linear minefield defense consisting of three layers: pressure mines in the SZ, tilt-rod mines in the VSW/SZ, and magnetic influence mines in the VSW. An influence mine is a mine

actuated by the effect of a target on some physical condition in the vicinity of the mine or on radiation emanating from the mine. A tilt-rod mine is an anti-landing mine actuated by direct pressure against a rod causing it to tilt to a set limit. A pressure mine has circuits that respond to direct pressure or the hydrodynamic field of the target (Surface Warfare Development Group 1995). Water depth was used as a context for categorizing the types of mines laid in particular regions. The mines were laid in a layered linear fashion, and the corresponding mine types and depths are depicted in Figure 2.

need for effective MCM. The basic landing force used in all three scenarios consists of 23 Amphibious Assault Vehicles (AAVs), 9 LCACs, and 11 Landing Crafts Utility (LCUs). The AAVs are split into two distinct task forces, the first consisting of 11 AAVs and the second consisting of 12 AAVs. Closely following the AAVs are the LCACs that ingress in column formation through one lane and egress through another lane.

Kernal Blitz 95 served as the test ground for the MCM used in the traditional scenario. This scenario incorporates a current MCM

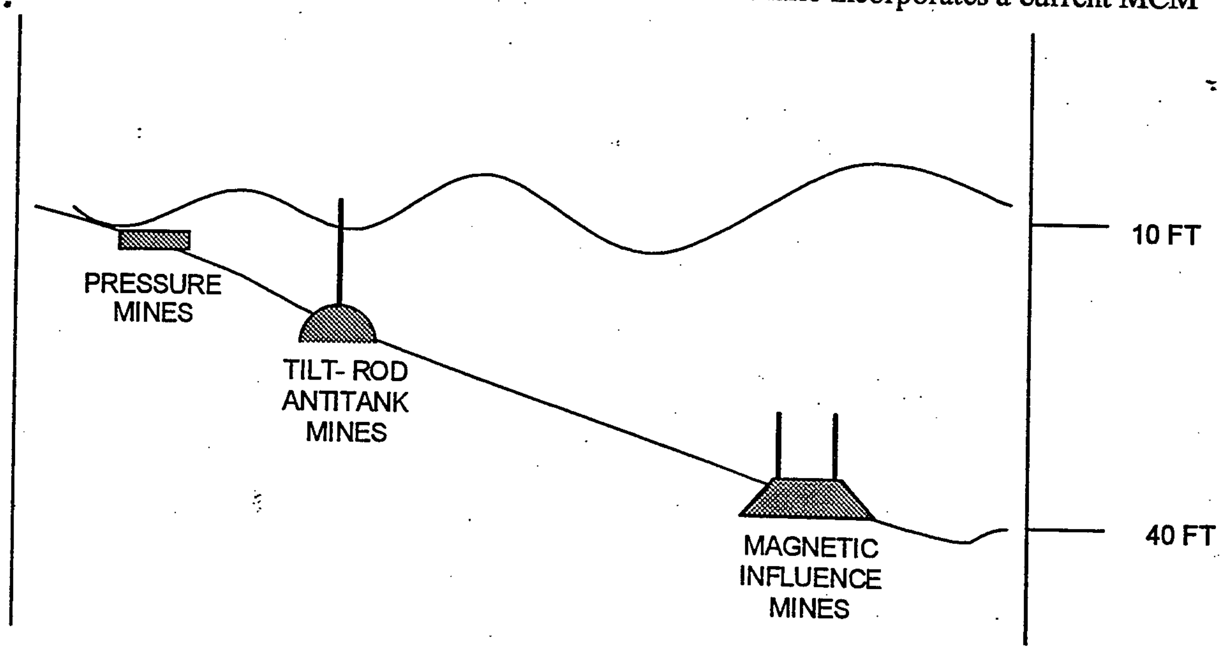

Figure 2. VSW and SZ Mines by Depth

The bull-breaching scenario serves as a baseline to gauge the relative effectiveness of the other two scenarios: the traditional scenario, and the ALUV scenario. The bull-breaching scenario simulates an amphibious landing through mined littoral zones with no breaching operations being conducted prior to the assault. This scenario demonstrates the devastating effect that a minefield can have on a force that proceeds through without prior clearing and emphasizes the

technique and a developmental MCM technique that has yet to be employed in a real operational setting. MCM is provided by four MH-53E Sea Dragon helicopters towing Mk 105 magnetic sweep hydrofoils clearing the VSW. Next, two LCACs (one per lane) each containing twelve M-58 line charges, breach a lane in the SZ. Upon clearing, the AAV task force transits through the cleared lanes and is followed by the LCACs.

The final scenario, the ALUV scenario, replicates the traditional scenario except that ALUVs replace the Sea Dragon helicopters and the LCACs with line charges. This scenario uses 358 ALUVs against 358 mines. Again after clearing, the AAV task force and LCACs conduct a landing

Measures of Effectiveness

Three measures of effectiveness (MOEs) were selected to compare scenarios: Average Number of LF Kills by Mine Type, Average Combat Power Ashore, and Dollar Savings.

The Average Number of LF Kills by Mine Type is an indicator of the relative success of the "in-stride" MCM operation and further provides data on a MCM's effectiveness against a specific type of mine. For this MOE we average the number of kills in each of the 16 simulation runs. The kills are classified by the mine type responsible.

Average Combat Power Ashore is another measure of the "in-stride" MCM effectiveness. To calculate this MOE the mean number of surviving landing craft was recorded for each simulation run. Note that each LCAC had two opportunities to be killed, inbound and outbound. If the LCAC survived its inbound journey, it was able to offload its contents at the landing site and thus is included as a "surviving landing craft". The outbound fate of the LCAC provided no information for the calculation of this MOE. AAVs transit the mined landing craft lanes only once; therefore, they project combat power ashore only if they survive their single transit to the shore.

We compute the approximate dollar savings for each MCM by considering the actual cost of each AAV and LCAC in the LF and the difference in the LF kill rates between scenarios. This MOE measures the total cost of landing craft losses and not the cost of the particular MCM however it provides some indication as to the materiel value of a particular MCM. The following dollar costs were used to calculate this MOE: \$27 million/LCAC (Burlage 1996) and \$2.5 million/AAV (Headquarters Marine Corps 1996).

DATA ANALYSIS

Statistical Evaluation of the LF Kills MOE

Since the observed samples from the scenarios have unknown distributions, we employed the Mann-Whitney U Test, a non-parametric test which can be used to evaluate two independent samples to determine which population mean exceeds the other. This test is conducted by ranking the observed values and analyzing the ranks instead of the original data. In an interrogative sense, the authors seek answers to three questions:

1. Is bull-breaching (MCM 1) more effective than traditional breaching (MCM 2)?
2. Is bull-breaching (MCM 1) more effective than ALUV breaching (MCM 3)?
3. Is traditional breaching (MCM 2) more effective than ALUV breaching (MCM 3)?

Translating to statistical hypotheses gives a null hypothesis:

H_0: The population means are equal.

The null hypothesis is tested against three distinct alternative hypotheses, using LF kills per scenario as a measure:

H_{A1}: The population mean of bull-breaching (MCM 1) is greater than that of traditional breaching (MCM 2)

H_{A2}: The population mean of bull-breaching (MCM 1) is greater than that of ALUV breaching (MCM 3)

H_{A3}: The population mean of traditional breaching (MCM 2) is greater than that of ALUV breaching (MCM 3)

After completing the runs we can examine the outcomes to see if they support the assertion that the null hypothesis should be rejected. The null hypothesis will be rejected at a significance level of $\alpha = 0.05$ only if the observed value of U is less than the critical value of 83. This number is obtained from a standard table of critical values for the Mann-Whitney U statistic (see Tannis 1987 for details on the Mann-Whitney U test).

H_0 versus H_{A1}

Table 1 contains the results of the Mann-Whitney U Test for this case. The authors used the ranked sums and the sample sizes to calculate an observed U statistic of 3. Since 3 is much less than 83 and the ranked mean LF kills of the bull-breaching scenario exceed that of the traditional scenario, H_0 is rejected and H_{A1} is assumed. Note that the p-value that appears in the table is the probability of incorrectly rejecting the null hypothesis. This small p-value indicates that relative to LF Kills, the traditional breaching is more effective than bull-breaching.

Mann-Whitney U Test			
Level	Sample Size	Ranked Sum	Ranked Mean LF Kills
Bull	16	389	24.3125
Traditional	16	139	8.6875
Observed U	Prob > U (p-value)		
3	<0.0001		

Table 1. Mann-Whitney U Test of H_o versus H_{A1}

H_0 versus H_{A2}

Table 2 contains the results of the Mann-Whitney U Test for this case. In this case we calculate an observed U statistic of zero. Incidentally, a U statistic of zero indicates that no rank in the lower ranking groups exceeds any ranking in the higher ranking group. Since zero is much less than 83 and the ranked mean LF kills of the bull-breaching scenario exceed that of the ALUV scenario, H_0 is rejected and H_{A2} is assumed. Again, note the extremely small p-value in the table. We conclude that relative to LF Kills, ALUV breaching is a more effective MCM than bull-breaching.

Mann-Whitney U Test			
Level	Sample Size	Ranked Sum	Ranked Mean LF Kills
Bull	16	136	8.5
Traditional	16	392	24.5
Observed U	Prob > U (p-value)		
0	<0.0001		

Table 2. Mann-Whitney U Test of H_o versus H_{A2}

H_0 versus H_{A3}

Table 3 contains the results of the Mann-Whitney U Test for this case. In this case we calculate an observed U statistic of 7.5 which is much less than 83, and since the ranked mean LF kills of the traditional scenario exceed that of the of the ALUV scenario, H_0 is rejected and H_{A3} is assumed. Again, the p-value is extremely small. We, therefore conclude with reasonable certainty that relative to LF Kills, ALUV breaching is a more effective MCM than traditional breaching.

Mann-Whitney U Test			
Level	Sample Size	Ranked Sum	Ranked Mean LF Kills
Bull	16	143.5	8.9688
Traditional	16	384.5	24.0313
Observed U	Prob > U (p-value)		
7.5	<0.0001		

Table 3. Mann-Whitney U Test of H_o versus H_{A3}

The Mann-Whitney U Test supports the intuitive notion that ALUV breaching is a more effective MCM compared to both traditional and bull-breaching. Further analysis of LF Kills by specific mine types is presented in Figure 3. Recall that the LF is composed of 32 landing craft (23 AAVs and 9 LCACs). Figure 3 displays a comparison of average landing force (LF) kills by mine type and by scenario. The figure reveals that

pressure mines had the greatest effect on the LF in the ALUV scenario (although not by a great margin). Magnetic influence mines (MGMs), tilt-rod mines (T-RMs), and pressure mines (PMs) accounted for 1.37, 1.13, and 3.5 of the total average of 6 LF kills in the ALUV scenario. PMs also had the greatest effect on the LF in the traditional scenario (this time by a larger margin). MGMs, T-RMs, and PMs respectively accounted for 2.3, 2.8, and 7.45 of the total average of 12.55 LF kills in the traditional scenario. The bull-breaching scenario had a fairly even distribution of kills between mine types. MGMs, T-RMs, and PMs respectively accounted for 7.2, 6.6, and 6.8 of the total average of 20.6 LF kills in the bull-breaching scenario.

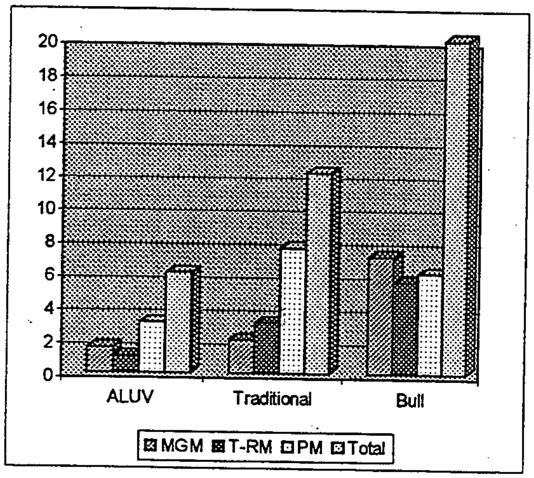

Figure 3. Average LF Kills by Mine Type and Scenario

When comparing the three scenarios it becomes evident that the total average number of LF kills in the bull-breaching scenario exceeds the total average number of LF kills in the traditional scenario. Additionally, the total average number of LF kills in the traditional scenario exceeds the total average number of LF kills in the ALUV scenario. Furthermore, the same result holds when comparing the number of LF kills induced by each mine type, with one exception - PM kills when comparing the bull-breaching scenario and the traditional scenario. One possible explanation as to why the number of PM kills is approximately equal in these two scenarios is that in three of the sixteen traditional scenario runs, the MCM assets did not make it to the SZ to clear a lane for the LF. In particular, the AAVs with line charges were killed by MGMs in the VSW. Additionally, when the SZ MCM of the traditional scenario failed to reach the SZ and hence could not perform their mission, many were rendered ineffective by T-RMs. Not surprisingly, these assets did not clear lanes through PMs.

Notice that the use of a high-resolution simulation is what makes it possible to draw inferences of this type. Indeed, whenever we have noted seemingly anomalous effects, the ability to look back at the actual runs proves the value of the approach. This kind of tactical feedback would allow an analyst to refine their line of inquiry if needed. For instance, one could now go back and compile another set of statistics using only data from runs where the MCM assets completed their tasks (although we do not do so here). We have found this to be an extremely valuable modeling and analysis tool.

These results indicate, as is well known in the MCM community, that the SZ still poses a formidable challenge for traditional MCM assets. The comparative analysis suggests that ALUVs hold great promise as an effective in-stride MCM.

Combat Power Ashore MOE

Figure 4 diagrams the percentage of combat power ashore by scenario. To develop this diagram, the authors calculated the average number of surviving landing craft for each scenario. This MOE suggests that the ALUVs are approximately 20% more

effective than the traditional method of clearing a mined landing lane. The fact that only 45% of the force reached the shore in the bull-breaching scenario emphasizes the urgent need for effective MCM in the VSW/SZ.

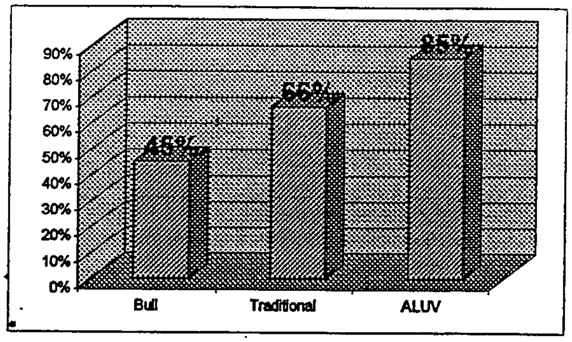

Figure 4. Average Percentage of Combat Power Ashore by Scenario

Dollar Savings MOE

Figure 5 shows the approximate fiscal savings (in millions of dollars) using one MCM vice another. These numbers are computed by comparing the number of landing craft saved when employing different MCM. Recall that a LCAC costs $27 million and an AAV costs $2.5 million from the discussion of the Dollar Savings MOE above. The numbers presented in Table 4 were used to construct Figure 5.

Number of Landing Craft Saved when Employing Differing MCMs			
Landing Craft	Traditional vice Bull	ALUV vice Bull	ALUV vice Traditional
AAV	6	10	5
LCAC	3	5	2

Table 4. Number of Landing Craft Saved by MCM

This cost analysis suggests that ALUVs are the most effective MCM in terms of minimizing the costs incurred from landing craft losses. The precise dollar figures are important in that they indicate the opportunity value of an ALUV approach. Indeed, a common criticism of this approach is that "it is cost ineffective to destroy a $3 mine with a $1000 ALUV" (the current projected cost). However, a more meaningful statement is that "it is cost ineffective to destroy a $3 mine with a $27 million dollar LCAC when you can do it with a $1000 ALUV."

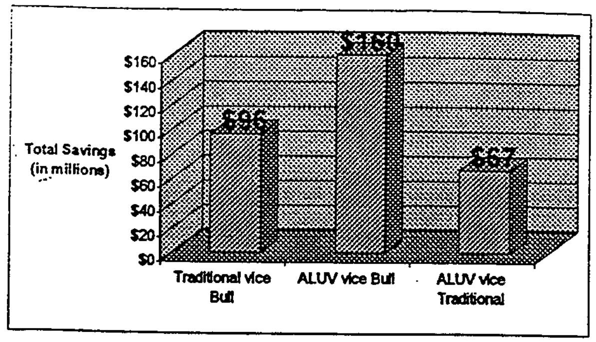

Figure 5. Cost Savings for Different MCM

SUMMARY AND CONCLUSIONS

This paper has sought to evaluate the tactical effectiveness of the Autonomous Legged Underwater Vehicle (ALUV) as a mine countermeasure (MCM) in the very shallow water and the surf zone relative to current Naval Service capabilities for hunting and neutralizing mines in these regions. Using the Janus combat simulation, the authors developed three scenarios which highlight the differences in effectiveness of bulling a landing force through a mined landing zone, landing a force through a mined landing zone after employing current or "traditional" MCM methods, and landing a force through a mined landing zone after employing ALUVs as a MCM. The scenarios were identical, other than the MCM employed. The Kernal Blitz 95 exercise guided the development of the scenarios and provided the composition of the landing force. To concentrate the modeling effort on the analysis of the MCM, the authors assumed that the amphibious landing force encountered no opposing enemy fire. We then ran sixteen independent trials of each scenario to generate the data to be used in our later analysis.

The authors then focused on three measures of effectiveness: landing force kills by scenario and mine type, combat power ashore, and the total cost of landing craft losses. Landing force kills by scenario revealed that the ALUV scenario suffered an average of six kills, while the traditional and bull-breaching scenarios suffered an average of approximately 13 and 21 kills respectively. Pressure mines proved most lethal in the ALUV and traditional scenarios, while the bull-breaching scenario saw a fairly even distribution of kills among the three mine types (pressure mines, tilt-rod mines, and magnetic influence mines). We used a non-parametric test to compare the landing force kill data for the three scenarios and found that the differences were statistically significant. The results indicate that ALUV breaching was the most effective MCM in the sense of minimizing the number of landing force kills due to mines.

The combat power ashore analysis showed that on average 85% of the ALUV landing force safely made it to shore, while the average percentage of combat power ashore in the traditional scenario and bull-breaching scenario was 66% and 45%, respectively. The cost analysis suggested that there is a fiscal saving when employing ALUVs vice traditional MCM or using no MCM.

This study indicates that ALUVs, as modeled, counter mines more effectively than current countermeasures employed in the VSW/SZ. This conclusion is drawn with the understanding that modeling and simulation is a tool possessing strengths and limitations. Its limitations lie in its inability to re-create actual physical conditions and the "fog" of war. It is, however, a valuable tool for gaining insights into many of the questions involved in combat analysis. In sum, this analysis suggests the Naval Service should continue to explore ALUVs as a possible solution to the VSW/SZ mine countermeasures problem.

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